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Ceramic alumina substrates for high-temperature gas sensors – Implications for applicability

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Abstract

In the field of gas sensors and high temperature flow sensors, thick-film based structures play a key role, particularly in harsh environments. Their substrates have to be electrically insulating and chemically inert. Alumina substrates are often considered as ideal sensor substrates. However, neither their electrical resistivity nor their chemical inertness is ideal. Even the thermal conductivity is that temperature dependent that one has to consider it when modeling temperature profiles. Measurements on the resistivity and the thermal conductivity between room temperature and 800 °C of alumina substrates are presented in this contribution together with data how the resistance of naked alumina substrates is affected by NO_2.

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Keywords: ceramic substrates, alumina, gas sensors, electrical resitivity, thermal conductivity, LTCC

1. Introduction

In the field of gas sensors and high temperature flow sensors, thick-film based structures play a key role, particularly if the sensors are applied in harsh environments [1-4]. The substrates have to be electrically insulating, and their resistivity should not depend on chemical species in the ambience. To design gas sensors with a uniform temperature distribution, the thermal conductivity, λ, of the substrates has to be high. However, to decouple two different heat sources, as it is the case in sensors measuring heat differences (calorimeter, flow sensors), a low λ is preferred. In this

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case, the substrates manufactured in LTCC technology seem to be more suitable due to their low thermal conductivity [5-7].

Whereas increasingly often LTCC ceramics are used to build gas sensors [8-12], in this study we focus on commercial alumina substrates, as they are standard for thick and thin film electronic devices.

2. Thermal conductivity

For thermal calculations, it is mandatory to know $\lambda(T)$ of the substrates [13]. The thermal conductivity was determined using LFA1000 Laser Flash device (Linseis, Germany). We measured the thermal conductivity of such substrates between room temperature and 800 °C (Fig. 1). The results in Fig. 1 have strong implications on the design of gas sensors. First of all, the $\lambda(T)$-behavior needs to be considered when calculating temperature profiles and/or heater power for alumina meso hot-plates [14,15]. Since the thermal conductivity of 96% alumina decreases by a factor of 3 from 21.6 W/(m·K) at room temperature down to 7.6 W/(m·K) at 800 °C and in the case of 99.99 % alumina by a factor of 3 from 29.2 W/(m·K) to 9.6 W/(m·K) at 500 °C, neglecting the temperature dependence yields strong errors.

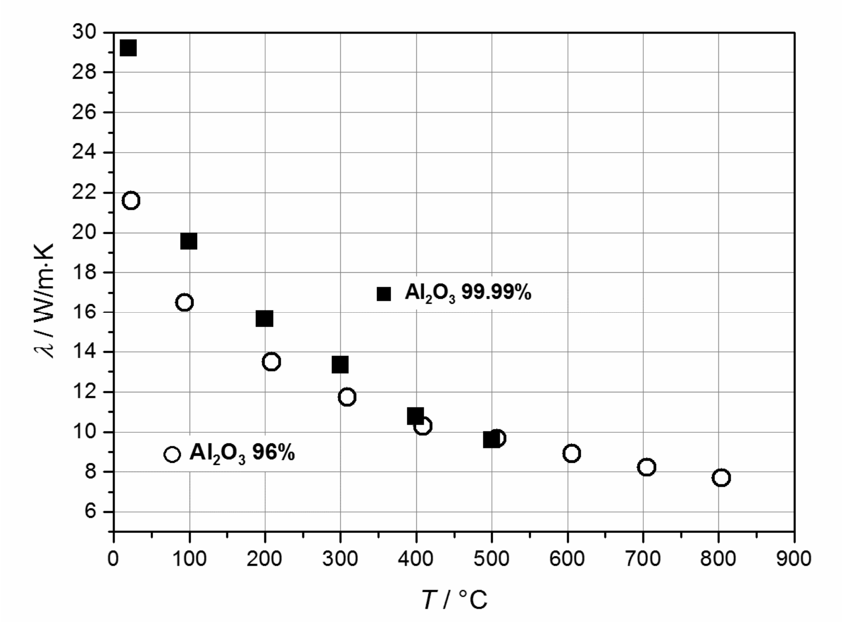

Fig. 1. Comparison of temperature dependency of the thermal conductivity of 96% and 99.99% alumina substrates.

3. Electrical resistivity

The specific resistance, ρ, calculated from the impedance, was also determined in the same temperature range (Fig. 2). The drastically reduced electrical insulation behavior at higher temperature needs to be considered as well. For instance, the electrical resistivity of the 96% alumina substrate decreases from > 10^{14} Ω·cm at room temperature to 10^7 Ω·cm at 700 °C. It is clear that especially high-ohmic gas sensor films cannot be measured correctly when using 96% alumina substrates. The situation gets better when 99.6% alumina (commercial thin film) substrates are used. Their resistivity is two orders of magnitude higher than the substrates made of 96% alumina.

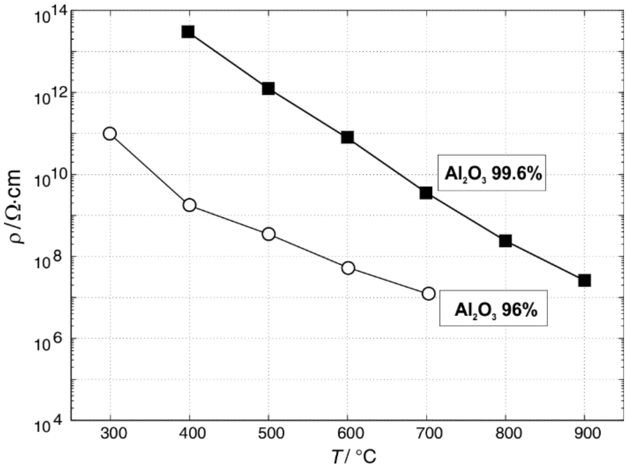

Fig. 2. Temperature dependency of electrical conductivity of 96% and 99.6% alumina substrate (modified after [16]).

4. Inertness of alumina substrates

Furthermore, we investigated the chemical inertness of alumina substrates (Fig. 3). For the latter, we used screen-printed interdigital electrodes (lines and spaces 100 µm) and tested the response of the impedance towards oxidizing or reducing gases. It is interesting and astonishing to see that at around 200°C to 350 °C, such commercial substrates change their electrical conductivity when NO_2 is applied. This is not fully astonishing if one considers that alumina is applied in automotive NO_x adsorber catalysts where it is discussed as a NO_x storing material in this temperature region [17].

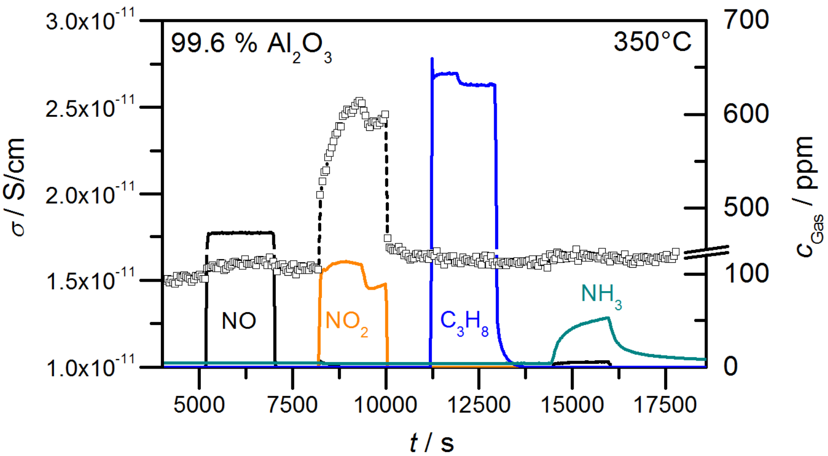

Fig. 3. Electrical conductivity calculated from impedance of uncoated 99.6% alumina at 350 °C as a response of different concentrations of reducing and oxidizing gases in the ambience.

5. Conclusions

The temperature dependency of properties of ceramic substrate applied for gas sensors is very often neglected, mostly at the very first stage of the design process. However, it is shown here that it may affect the proper functionality of the sensor.

Underestimation of thermal conductivity changes may cause improper temperature distributions in the area of the gas sensitive layers and may consequently decrease the sensitivity or the selectivity (if temperature dependent) of the sensor. Neglecting the relatively low electrical resistivity of alumina at temperature above 600 °C can have more important consequences - in the worst case, the resistivity changes of the alumina substrate instead of the gas sensitive film will be measured [4]. Special care has to be taken to avoid coupling of currents through a heater structure on the opposite side of a sensor with the sensitive film. Some authors even applied an equipotential layer between upper side (sensor film side) and lower side (heater side) due to the low electrical insulating behavior of alumina substrates at higher temperature [18].

Special care has to be taken in the case of conductometric or impedimetric NO_2 sensing. Sometimes in literature, one finds gas sensor data with high resistances in the range of hundreds of megaohms, especially for tungsten oxide as a selective NO_2 sensor. Considering the conductivity changes calculated from the impedance response of uncovered 99.6% alumina towards NO_2 (Fig. 3), we recommend to measure always also uncoated substrates before interpreting the sensor results in terms of chemical sorption processes that occur on the functional gas sensitive film.

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